

In-situ Shadow-Mask Epitaxy of Superconductor/Semiconductor Hybrid Structures

Duration: 6 months starting from March 2027
Salary: ~650 EUR/month (legal internship stipend)
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Context of the project: When a superconductor is placed in contact with a semiconductor, Cooper pairs leak into the semiconductor through the proximity effect. The resulting hybrid combines the gate tunability and strong spin-orbit coupling of III-V semiconductors such as InAs or InSb with the macroscopic quantum coherence of superconductors such as Al or Nb.

Such hybrids are the building blocks of several emerging quantum technologies. They enable gate-tunable superconducting qubits, in which the Josephson energy is controlled by an electrostatic gate rather than by magnetic flux [1], and they provide a route towards topological superconductivity and Majorana-based, intrinsically protected qubits [2,3]. They are also at the heart of Josephson field-effect transistors and superconducting diodes for cryogenic, low-dissipation electronics, of Andreev spin qubits and tunable couplers for scalable superconducting quantum processors, and of quantum sensors and parametric amplifiers based on gate-tunable Josephson junctions.

The performance of all these devices depends critically on the quality of the superconductor/semiconductor interface. Pioneering work showed that growing the metal epitaxially, in the same ultra-high vacuum (UHV) run as the semiconductor, yields atomically sharp interfaces and a "hard" induced superconducting gap [2,3]. However, devices then require the metal to be removed locally by wet etching, which damages the semiconductor surface and introduces device-to-device variability. In-situ patterning by shadow masks avoids this step entirely: the metal is deposited only where it is needed, and the interface is never exposed to air or to chemicals [4].

The project: We will develop a fully in-situ route to patterned superconductor/semiconductor hybrids using silicon nitride (SiN) stencil masks inside the new Octoplus MBE cluster at C2N [8]. The cluster links two 2-inch MBE reactors through a UHV tunnel: one grows III-V heterostructures, the other deposits superconducting and ferromagnetic metals. The metal chamber has a dedicated mask station for localized deposition and a cold finger allowing deposition down to 100 K. Samples therefore move from semiconductor growth to metal deposition without ever leaving UHV.

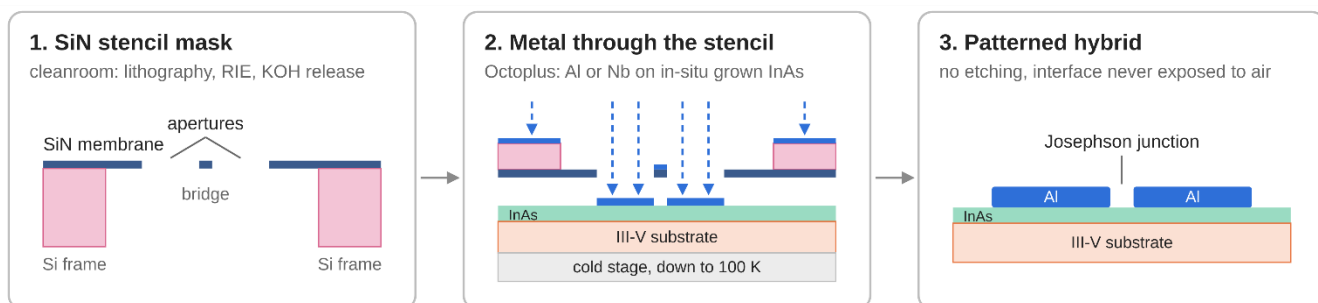


Figure 1. Fabrication process. The SiN stencil made in the cleanroom (1) is loaded in the mask station of the Octoplus cluster; after in-situ growth of the III-V layer and UHV transfer, the metal reaches the semiconductor only through the apertures (2), leaving a narrow uncovered gap under the SiN bridge that forms a Josephson junction (3).

The stencil masks are free-standing, low-stress SiN membranes in which apertures are opened by lithography and etching [6,7]. Placed above the freshly grown semiconductor, they let the metal reach the surface only through the apertures, defining contacts, Josephson junctions or superconducting islands directly during growth (Figure 1). Low-temperature deposition

limits adatom diffusion, which keeps metal edges sharp and favours continuous, epitaxial films [2,5]. The key open questions are:

- **Resolution:** what is the smallest feature (target: from a few μm down to ~ 100 nm) and the narrowest gap between two electrodes (the Josephson junction length) that can be transferred reliably?
- **Edge definition:** how do the mask–substrate gap, the source geometry and the substrate temperature broaden the pattern edges or create a halo of metal around them?
- **Epitaxy:** does the metal grown through the stencil keep the same crystalline quality and epitaxial relationship with the semiconductor as an unpatterned film?

Master 2 internship: The student will take the stencil masks from design to first hybrid structures, with a strong hands-on component in the C2N cleanroom. The internship will be organised in three stages:

1. **Mask fabrication in the C2N cleanroom.** Design test patterns (lines, dots, gaps and Josephson-junction geometries of decreasing size), then fabricate free-standing SiN membranes on silicon: SiN deposition, optical and electron-beam lithography, reactive ion etching of the apertures and backside wet etching (KOH) to release the membranes.
2. **Metal deposition in the OctoPlus cluster.** With the MBE team, mount the masks in the mask station and deposit superconducting metals (Al, Nb) on III-V substrates and heterostructures, varying the substrate temperature, the mask–substrate distance and the film thickness.
3. **Characterization.** Measure the transferred features by optical microscopy, SEM and AFM to quantify the resolution, edge broadening and pattern fidelity. Assess crystalline quality and epitaxy by X-ray diffraction and, on selected samples, cross-sectional TEM of the metal/semiconductor interface.

The expected outcome is a validated stencil process with known resolution limits and design rules, and a first set of epitaxial superconductor/semiconductor structures ready for low-temperature transport measurements. The student will acquire skills in cleanroom micro- and nanofabrication, ultra-high vacuum epitaxy and advanced structural characterization, in a multidisciplinary environment bridging materials growth and quantum devices.

Candidate profile: Highly motivated candidates enrolled in a master's degree or equivalent, with a background in physics, materials science or engineering. Prior cleanroom training (lithography, etching, thin-film deposition) is a strong advantage. Interest in experimental work, vacuum techniques and quantum materials is expected.

Application procedure: For additional information about the project and/or the recruitment process, please contact Maryam Sadeghiyan and Federico PANCIERA. Applications should include a CV and recent transcripts.

References

- [1] T. W. Larsen et al., *Semiconductor-Nanowire-Based Superconducting Qubit*, Phys. Rev. Lett. 115, 127001 (2015).
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- [4] D. J. Carrad et al., [Shadow epitaxy for in situ growth of generic semiconductor/superconductor hybrids](#), Adv. Mater. 32, 1908411 (2020).
- [5] J. Shabani et al., *Two-dimensional epitaxial superconductor–semiconductor heterostructures: A platform for topological superconducting networks*, Phys. Rev. B 93, 155402 (2016).
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